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THE INTERACTION OF CHROMOSTEREOPSIS AND STEREOPSIS IN STEREOSCCPIC CRT DISPLAYS

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

By

JAMES ENNIS MCCLAIN
B.S., United States Air Force Academy, 1986

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY James E. McClain ENTITLED The Interaction of Chromostereopsis and Stereopsis in Stereoscopic CRT Displays BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Thesis Director

Department Chair

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Dean of the School of Graduate
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ABSTRACT

McClain, James Ennis. M.S., Department of Biomedical and Human Factors Engineering, 1989. The Interaction of Chromostereopsis and Stereopsis in Stereoscopic CRT Displays.

With the increased complexity in aircraft and space system information display capabilities, conventional two-dimensional (2-D) displays will eventually be replaced by more capable 3-D stereoscopic displays. 3-D stereoscopic displays allow the vehicle operator to more effectively interact with an increasingly dynamic environment by presenting information consistent with the operator's perceptual experience and stereotypes.

Important to the development of stereoscopic 3-D displays is the interaction of perceived depth created by hues (chromostereopsis) and perceived depth created by presenting different images of a single object to the left and right eye of the observer (stereopsis). Theory and past research have addressed the causes and interactions of chromostereopsis and the natural stereoscopic process humans utilize when observing one or more objects in real space. However, with stereoscopic cathode ray tubes (CRTs), 3-D objects are physically located on a single plane (the CRT screen) and the stereoscopic process of the observer's

visual system is artificially stimulated to perceive depth via methods of right and left image separation. The purpose of this research is to evaluate the interaction of chromostereopsis and stereopsis on a stereoscopic CRT by determining the level of accuracy with which subjects can properly interpret the relative depth differences of adjacent symbols containing different levels of hue and stereoscopic disparity. Disparity is the measure of difference, in units of arc minutes, between the left and right images of an object presented on a stereoscopic display which results in the presentation of artificial depth.

The two independent variables in the study consisted of six levels of hue and seven levels of disparity, with the dependent variable being the accuracy of subject interpretations of depth based on the discrimination of disparity levels alone.

This research demonstrated that hue, disparity, and the interaction of hue and disparity significantly influenced one's perception of depth on a stereoscopic monitor.

These results suggest that caution should be exercised by the stereoscopic 3-D display format designer when choosing hues to represent images located in close proximity on a stereoscopic display. Due to the chromostereoscopic effect on the perception of depth, the use of hues on

extreme ends of the color spectrum should not be used in situations where less than 3.39 arc minutes of disparity difference is being portrayed on a stereoscopic display, unless the hues are consistently being used to alter the depth presented by stereoscopic disparity, or the depth due to certain hues is consistently nullified by altering disparity levels accordingly.

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The deepest thanks and appreciation goes to Drs. Anthony Cacioppo and John Reising for their guidance and assistance in the development and completion of this thesis research. Sincere appreciation also goes to Lt. Ronald Opp for his aid in software development, and to the Flight Dynamics Laboratory and all its members for allowing this research to be conducted at that facility. Finally, the greatest thanks and appreciation goes to my Lord Jesus Christ for his love, leadership, guidance, and mercy.

I. INTRODUCTION

In the modern air combat environment, the pilot's ability to make time-critical decisions associated with three dimensional space may result in his survival. Because of the increased complexity and dynamics of such an environment, the capability of conventional two-dimensional (2-D) displays to provide the pilot with the necessary three-dimensional (3-D) situational awareness is questioned.

A 3-D display which performs well under laboratory conditions and holds promise for providing situational awareness in future aircraft applications is the stereoscopic display. Stereoscopic displays produce an artificial stereopsis effect in the observer by presenting different left and right images to corresponding eyes via temporal or polarized separation. Stereopsis is defined as the natural perception of depth originating from the binocular disparity of our visual system caused by the separation of our eyes. Different images presented to each eye by a stereoscopic display produces binocular disparity. This disparity between the left and right images of the eye in turn generates the perception of depth such that larger positive or negative levels of disparity result in greater positive or negative perceptions of depth. Operationally

negative disparities come out of the screen while positive disparities go into the screen.

Important to stereoscopic displays is the interaction of depth perception based on hues used in the display formats and the perception of depth based on stereopsis. Chromostereopsis (Vos, 1963) refers to the illusion of depth experienced when variously colored patches located on a single plane surface are viewed binocularly. Depending on individual biases, reds (longer wavelength colors) are displaced toward an observer while blues (shorter wavelength colors) are displaced away from the observer.

In stereoscopic display applications, determining to what extent chromostereopsis affects stereopsis, and predicting the points at which different hues may falsely alter intended stereoscopic depth perception is of primary concern.

The objective of this research is to evaluate the chromostereoscopic effect of different hues on near threshold levels of stereoscopic disparity placed on adjacent stimuli using a stereoscopic 3-D display.

II. BACKGROUND

CHROMOSTEREOPSIS

Chromostereopsis (color stereoscopy) is a phenomenon of the human visual system by which two or more differently colored objects, placed in close proximity to one another in the same plane, are generally perceived to be at different distances. It should be recognized that chromostereopsis does not relate to the effects of atmospheric attenuation. With atmospheric attenuation, the scattering and absorbtion of light rays by the atmosphere, as a function of distance, causes bright colors to be associated with closer objects and dull colors with more distant objects. This effect is often used in art to portray depth; however does not represent chromostereopsis.

As noted by Sundet (1972), chromostereopsis can be perceived under both monocular and binocular visual conditions. Yet, due to the small volume of information concerning monocular vision, only binocular (stereoscopic) data related to chromostereopsis will be discussed.

Kishto (1965), along with numerous other authors found that the perceived depth of colors varies directly with the wavelength of the color. In most cases, assuming all other parameters of the colors are held constant, longer

wavelength colors are perceived closer than shorter wavelength colors. However, with some viewers, this perceived order of color depth is reversed, and with a smaller percentage of viewers, the chromostereoscopic phenomenon is lacking. The remainder of this section will address the causes of chromostereopsis and the reasons for observer inconsistencies within this phenomenon.

THE BRUECKE-EINTHOVEN THEORY OF CHROMOSTEREOPSIS

Chromostereopsis was first discovered and explained by Bruecke (1868) and Einthoven (1885), (cited in Sundet, 1972; Vos, 1963). The Bruecke-Einthoven theory suggests that chromostereopsis is born out of the axial chromatic aberration of the eye and asymmetry in the dioptic system.

In order to understand how these characteristics create the phenomenon of chromostereopsis, it must first be known that the human eye is not symmetric. In viewing Figure 1, note that the optic axis is a theoretical line perpendicular to the cornea that divides the eye in equal halves, and that the cornea and lens do not share it as their common axis. The visual axis is a line that represents light traveling from the point of fixation to the fovea. If one assumes the visual system of the eye is localized at the cornea, it is evident that the visual axis transverses the pupil from the nasal side and then the optic and visual axis diverge (Vos, 1960; Owens & Leibowitz, 1975). This divergence results because the cornea and lens

do not have a common axis. The fovea is not located symmetrically on the retina, but is usually offset to the temporal side of the optic axis, while the optic nerve is offset to the nasal side of the optic axis.

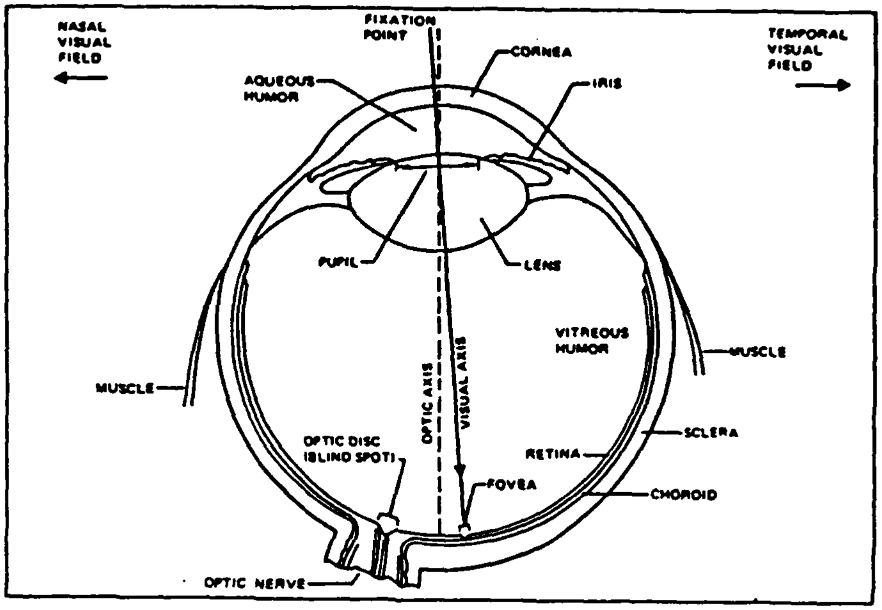

Fig. 1. Structure of the human eye. Farrell & Booth, 1984.

As an individual views an object, light is refracted by the cornea and lens. The difference in the axes of the cornea and lens causes the light entering the eye to be prismatically dispersed. This dispersion is a function of the wavelength of the light entering the eye such that longer wavelengths (e.g. yellow, magenta, and red) are refracted to the temporal side of the retina, while shorter wavelengths (e.g. blue and cyan) are refracted to the nasal side of the retina. Although this dispersion is small, the projection of colors onto different locations of the retina

results in longer wavelength colors appearing closer to an observer than shorter wavelength colors, especially in binocular viewing. This effect has been demonstrated in research performed by Kishto (1965), Kraft, Booth & Boucek (1972) and Sundet (1972) where red fields were perceived significantly closer than blue ones. Further, as Figure 2 depicts, the refractive power of the eye can be more than 2.5 diopters greater for light with a 400 nm wavelength (blue) than light with a 700 nm wavelength (red) (Farrell & Booth, 1984).

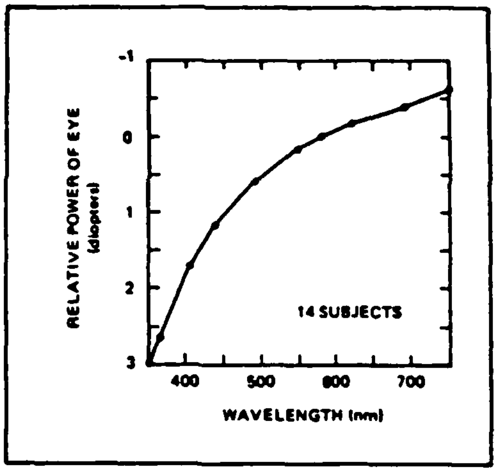

Fig. 2. Chromatic aberration of the eye. Farrell & Booth, 1984.

In efforts to evaluate the Bruecke-Einthoven theory of chromostereopsis, many researches have found supporting evidence based on geometric methods. First, Van Heel (1946) demonstrated that chromostereopsis is greatly reduced when corrective lenses are used to neutralize the chromatic aberration of the eye, which favors the Bruecke-Einthoven

theory. Second, Bedford (1957) and El Hage & Berny (1973) demonstrated that the eye's chromatic aberration changes as a function of wavelength and thus colors are refracted differentially in the eye. Third, Kishto (1965) demonstrated the effect of axial chromatic aberration by showing that the chromostereopsis phenomenon could be reversed or enhanced with the use of convergent or divergent prisms respectfully. Fourth, Owens & Leibowitz (1975) demonstrated that the use of artificial exit pupils decentered outward off a subject's pupil reverses chromostereopsis while inward decentering enhances chromostereopsis. This supports the Bruecke-Einthoven theory by illustrating the importance of interpupillary distance in relation to the eye's intervisual axes distance, which in turn affects the divergence of the visual and optical axes (Anderson & Kraft, 1977).

In addition, an increase in the depth effect as a result of increased observer distance, as noted by Kishto (1965), might be explained by the Bruecke-Einthoven theory if the angular dispersion of the rays within the eye were more or less constant.

THE STILES-CRAWFORD THEORY OF CHROMOSTEREOPSIS

Sufficient qualitative and quantitative data exists to indicate that chromostereopsis is due, in part, to axial chromatic aberration and asymmetry of the eye. Yet, if the Bruecke-Einthoven theory completely explained

chromostereopsis, it would be expected that most subjects would perceive red in front of blue since the visual axis almost always passes the pupil on the nasal side. However, as previously mentioned, this is not the case with all individuals, thus some other factor(s) must contribute to the chromostereoscopic phenomenon.

Vos (1960, 1963, 1966) suggests that differences in the chromostereopsis phenomenon, which cannot be explained by the Bruecke-Einthoven theory, can be resolved by understanding the luminous efficiency of rays entering the eye at different points. This luminous efficiency of the eye was first noted by Stiles and Crawford in 1933, and thus is called the Stiles-Crawford theory. As explained by Owens & Leibowitz (1975):

> the decentration of the effective optical axis of the eye, which results from the orientation of the foveal cones in relation to the pupil, tends to counteract the effects of chromatic dispersion of light on the retina, by reducing the sensitivity to the light rays that enter along the physical axis. That is, because of their orientation, the cones are most sensitive to light that enters the eye along an axis that lies on the opposite side of the visual axis from the optical axis.

Because of this key asymmetry in the orientation of foveal cones in relation to the pupil: the effective light center of the retina doesn't correspond with the pupil center, the luminous efficiency of light on the retina rapidly decreases as you move away from the asymmetric point of maximum luminous efficiency, and thus, rays that enter the center of the pupil are five to ten times more effective

then those entering near the outside boarder of the pupil.

As cited by Vos (1963), the Stiles-Crawford effect is an asymmetry in the visual system which provides an antagonistic effect in relation to the Bruecke-Einthoven theory. The antagonistic effect postulated by the Stiles-Crawford theory is directly related to the size of the pupil, and thus, the illumination of the visual field. If the size of the pupil is effectively made small (narrow beam) via high illumination or the use of small artificial pupils, the Stiles-Crawford effect is virtually eliminated. On the other hand, if the pupil is made large via low illumination or dilation, the Stiles-Crawford effect is enhanced and can overcome the Bruecke-Einthoven effect, thus causing a reversal in chromostereopsis such that blues will be seen in front of reds.

An example of the Stiles-Crawford effect can be found in Sundet (1972):

> As the visual axis transverses the pupil on the nasal side of the pupil center, a blue dot will be nasally displaced relative to the image of a red dot, wherefore the red dot will be perceived closer then the blue (Bruecke-Einthoven theory). As the pupils become significantly larger for what ever reason, the influence of differences in luminous efficiency across the retina will become more pronounced, and the visually effective part of the blue dot will shift from the pupil center to the eccentric point of maximum luminous efficiency, resulting in a reversal of the color stereoscopic effect (Stiles-Crawford theory).

Unlike the Bruecke-Einthoven theory, the Stiles-Crawford theory suggests that chromostereopsis can be

altered with changes in visual field illumination. It also explains inconsistencies of the chromostereoscopic effect between subjects. As again stated by Owens and Leibowitz (1975):

> Because there are individual differences in the magnitudes of both the angle and decentration of the pupil, and because the Stiles-Crawford effect is determined by the size of the natural pupil, which varies in size, it is not surprising that reports of the magnitude and even direction of chromostereopsis vary among different experimenters.

ADDITIONAL EXPLANATIONS OF THE REVERSAL EFFECT

While the Stiles-Crawford effect offers the most consistent explanation of the chromostereoscopic reversal found with differences in illumination, there are two other theories that merit discussion. First, Kishto (1965) suggested that an eccentric opening of the eye may lead to a decentering effect in which the pupil centers move toward the nasal side of the visual axis. However, no conclusive experimentation has proven this theory. Second, Katz (1935) (cited in Sundet, 1972) suggested that alternate depth perception cues may produce a reversal of chromostereopsis. Brightness of the color fields may yield blue colors more "insistent", and hence cause the reversal effect. Nevertheless, experimentation performed by Sundet (1972) demonstrated that the reversal could not be explained in terms of secondary cues. This is not to say that other color related cues, such as brightness, do not create the depth perception differences in colors, but they simply

offer no explanation for the chromostereoscopic reversal effect.

AN ANTAGONISTIC RELATIONSHIP IN CHROMOSTEREOPSIS

Vos (1960, 1963) suggests that the Bruecke-Einthoven and Stiles-Crawford theories are complementary antagonistic effects which together result in a balanced perception of color depth in most observers. If this is true, one would expect a large population to have a relatively normal distribution of "chromostereoscopic bias" with a mean near zero. Chromostereoscopic bias indicates whether an observer perceived blue, red, or neither hue as closest. Although most studies have not shown a normal distribution of subject bias, a few studies such as Kraft & Anderson (1973) have produced subject responses that were approximately normally distributed around a mean of zero chromostereopsis.
It appears that the individual differences in chromostereopsis between individuals are a result of the relative dominance of the Bruecke-Einthoven and Stiles-Crawford effects. Those with a dominant Bruecke-Einthoven effect would generally perceive short wavelength colors behind long wavelength colors. Those with a dominant Stiles-Crawford effect would perceive the opposite, while those with balanced effects would perceive little of no chromostereopsis.

RELATIVE BRIGHTNESS OF CHROMATIC OBJECTS

The relative brightness of a hue can be related to the spatial properties of objects. As Ittelson (1960) points out, artists have used color for years to produce depth affects where warm, saturated, bright colors seem to approach the observer, while cold, unsaturated, dark colors recede. Experimental evidence shows that monocular perceived depth is affected by the relative brightness of the hue, where brighter colors appear closer in the absence of other strong cues (Sullivan, Harney & Martin, 1979). It appears that this effect is learned in humans, from experiencing changes in color due to atmospheric attenuation effects, not chromostereopsis. Atmospheric attenuation is the scattering and absorption of light and color by the atmosphere with increased viewing distance (Philips, 1984). Thus, the brightness of a colored object diminishes as viewing distance is increased. Provided the viewed object area remains constant, the relationship of brightness/intensity follows the formula: Brightness = $1 / \text{Distance}^2$ (Sullivan et al., 1979).

Since chromostereopsis and brightness are not identical effects, they can interact to produce interesting results. For example, the relative brightness of a hue can cause it to appear closer or farther than it would be perceived based on chromostereopsis alone.

STEREOPSIS

Stereopsis (binocular disparity) is the primary determinant in producing relative depth (Lipton, 1982; Uttal, 1983). Stereopsis relies on separation of the eyes such that the left and right images of an object(s), within both eye's overlapping visual field, are slightly offset from the other. This offset between the images in each eye (binocular disparity) depends on the fixed distance between the eyes and the distance to the object(s) being observed and is considered to be the factor that creates our sense of depth within stereopsis. The normal population can view objects using stereoscopic vision from approximately 6 inches to 30 feet (Spain, 1982). Loss of stereoscopic ability beyond approximately 30 feet occurs because the fixed separation between our eyes becomes geometrically too small to distinguish distance between objects (Lipton, 1982).

As reported by Uttal (1983), the threshold for correctly interpreting stereoscopic depth 75 percent of the time was approximately 20 seconds of angular disparity using a conventional two-stick measuring device as originally performed by Woodburne in 1934. However, subjects in the Uttal (1983) experiment had very long exposure times. More recent tests performed with less exposure time using Julesz-type random dot stereograms found that minimal determined disparities are more near 30 to 40 seconds of angular

disparity. It is important to note that two-stick devices used to measure stereopsis are luminance dependent while the Julesz-type device is devoid of any secondary cues such as luminance (Uttal, 1983).

This suggests that stereopsis may be affected by transient factors or cues present under certain viewing conditions. For example: individual differences, retinal location of images, lumination, viewing duration, stimulus density, familiarity of objects, chromostereopsis, brightness of the objects, and distance have all been found to affect stereopsis.

FACTORS AFFECTING STEREOPSIS

Approximately 2 to 10 percent of the general population are estimated not to experience stereopsis, and perhaps another 10 percent are deficient to some extent (Tolin, 1986). While little research has addressed this issue, a possible explanation could be ocular dominance in certain individuals. Ocular dominance is the over-emphasized use of one eye. Research by Piantanida (1980) found that mildly ocular dominant individuals had a small but measurable loss in the perception of stereopsis, while strong ocular dominance resulted in striking differences. Also, perception of stereoscopic depth was significantly reduced when luminance was reduced in the dominant eye compared to the non-dominant eye (Piantanida, 1980). This suggests that stereopsis might not be as effective for

individuals with a dominant eye. However, for some users that may have been considered stereoscopically blind due to ocular dominance, Tolin (1986) states that stereoscopic perception can increase with practice as long as binocular vision exists.

In discussing luminance, it is important to note that stereoscopic contour refers to the perception of a clearly defined edge attributed to an object or surface in space, and is essential to stereopsis (Gulick, 1976). While hue or saturation affect the determination of contours, the luminance of contours and possibly the comparison of luminance edges between eyes is most critical to stereopsis (Gulick, 1976 and Piantanida, 1981).

Retinal location affects stereopsis in that stereoscopic sensitivity is maximum at the fovea, and decreases as stimulation of the retina occurs at greater distances from the retina (Gulick, 1976). Tolin (1986) points out that stereoscopic acuity decreases by 50 percent or more for images just 2 degrees or more from the fovea.

Viewing duration and stimulus density are reciprocal factors affecting stereopsis. Longer viewing times yield better stereoscopic performance. Duration times below 0.4 to 0.2 seconds produces an abrupt decrease in correct perceptions, while the minimum time required to perceive stereopsis is 50 msec for an object made up of 100 dots placed on a back ground plane of 250 dots (Uttal, 1983).

Also, increased stimulus density allows easier discrimination of edges of contour between objects and their background.

Due to atmospheric attenuation, increased viewing distance and relative brightness (as previously mentioned) affect stereopsis proportional to the inverse square of the viewing distance (Fox, 1982).

Finally, familiar patterns or objects may be perceived at incorrect distances simply because of past experience (Rock, 1975). For example, if you have been repeatedly taught that the horse is in front of the cart, you may not notice a specific case when the cart is in front of the horse despite relevant depth cues.

THEORIES UNDERLYING STEREOPSIS

Of the numerous theories developed to explain stereopsis, two general schools of thought appear most promising. Muscular/physiological characteristics and cognitive processes.

The three primary physiological theories are Kepler's projection theory, Muller's theory of identical points, and Wheatstone's theory of visual disparity as stated in Gulick (1976). Kepler stated that the perceptual location of objects in space occurred at the point of intersection of the lines of sight of the projected retinal images of each eye. While his theory explained why we see only one image with two eyes, it didn't account for double vision.

Muller's theory countered Kepler's by suggesting the retinal images of objects that fall on corresponding retinal points will appear single in vision while those that don't will appear double. Here, while Muller's theory explained double vision, the process of single vision was not adequately described.

Finally, Charles Wheatstone formulated the currently accepted theory that stereoscopic depth perception resulted from visual disparity, or the difference between the images of the retinas. He found that single vision occurs when disparate retinal points are simultaneously stimulated, and that it is this kind of retinal stimulation that is responsible for the perception of depth. As stated by Rock (1975), Wheatstone reasoned that if binocular disparity is a depth cue, then the proof would consist of artificially synthesizing depth by presenting different pictures to the two eyes; pictures that differed in the same way that the retinal images to the two eyes differed in reality. From two 2-D pictures, an impression of depth was obtained where none was obtained from either picture alone and thus Wheatstone demonstrated that binocular disparity was a powerful depth cue.

In the twentieth century a new school of thought has arisen, Gestalt Psychology that no longer considers the anatomy of the eye to be the key in stereopsis.

Koffka (1935), an early Gestaltist, (cited in Gulick,

1976) states that stereopsis is the result of organizing processes within the brain. Briefly, he claimed that monocular form recognition was an essential condition for depth, and concluded that stereopsis could be generated by an apparent as well as real disparity of image contours since the primary process of stereopsis rests in the brain. While this cognitive organization theory does offer additional explanations for stereopsis, it remains incomplete in that it cannot fully explain single and double vision.

Most of the theories discussed above explain certain attributes of stereopsis well and appear to be supported by empirical data, yet not one can explain the entire process satisfactorily. One can assume that depth perception is a combination of complex physiological and cognitive processes that work together to create stereopsis.

DERIVATION OF HYPOTHESIS

Theory and past research have addressed the causes and interactions of chromostereopsis and the natural stereoscopic process humans utilize when observing one or more objects in real space. However, with stereoscopic cathode ray tubes (CRTs), 3-D objects are physically located on a single plane (the CRT screen) and the stereoscopic process of the observer's visual system is artificially stimulated to perceive depth via methods of right and left image separation. The purpose of this research is to

evaluate the interaction of chromostereopsis and stereopsis on a stereoscopic CRT by determining the level of accuracy with which subjects can properly interpret the relative depth differences of adjacent symbols containing different levels of hue and disparity.

The null hypothesis for this experiment is that hue has no effect on the perception of stereoscopic depth in a stereoscopic CRT.

III. METHODOLOGY

EXPERIMENTAL DESIGN

The experimental paradigm used for this research was a six by seven, repeated measures Analysis of Variance design (within subjects). The independent variables were hue and disparity. Hue had six levels which included: blue, cyan, green, yellow, magenta, and red. Disparity had seven levels which included: -3.39, -2.26, -1.13, 0, 1.13, 2.26, and 3.39 arc minutes of disparity.

An individual trial in the experiment consisted of a comparison of the relative depth of two JTIDS (Joint Tactical Information Display System) like symbols on a black background, with the subject response being recorded as correct or incorrect. (see Figure 3)

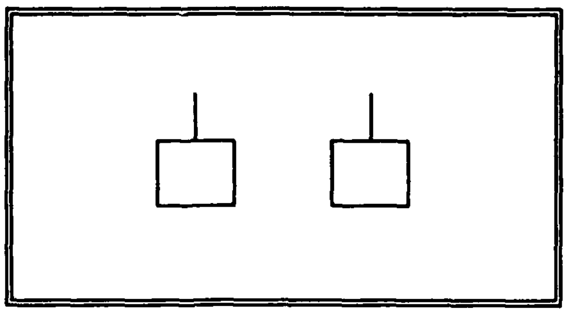

Fig. 3. Representation of JTIDS like symbols. The symbol pairs were centered on the screen. Each symbol was a two by two cm square with a two cm velocity vector pointing upward. The symbols were colored solid with one cm separation between them.

A trial set consisted of forty two individual trials, one for each factor level combination, presented in random order. Each subject received three different, counter-balanced trial sets (based on a balanced latin square), so that each subject had three exposures of the same forty five trial combinations for a total of one hundred and twenty six trials per subject.

The choice of hues used in this research was based on standard hues used in U.S. Air Force cockpit displays. The specific frequency distributions and Commission International de l'Eclairage (CIE) coordinates of each hue used was determined via spectra radiometer readings of each hue while being presented on a stereoscopic display, which can be seen in Appendix A. However, there is no frequency standard for such hues in the Air Force, and the hues used in this research are only representations of additive primary colors that may be used for the testing of future cockpit display formats.

The levels of disparity were determined by the minimum unit of view separation available on the stereoscopic 3-D monitor, which is one pixel (1 pixel = 1.13 arc minutes at a viewing distance of 29 inches). Zero disparity represents an object at the screen plane of the monitor, while negative and positive disparity values represent objects that were presented in-front-of and behind the screen plane of the monitor respectively.

The dependent variable was the accuracy (based only on disparity) with which the subject could correctly discriminate the relative depth differences of two adjacent JTIDS like symbols at a specific combination of hue and disparity.

SUBJECTS

Twenty Air Force and government employed personnel from Wright-Patterson AFB, Ohio were used as subjects in the experiment. The subjects were 50 percent male and 50 percent female and all possessed normal color vision, stereoscopic perception of at least 50 arc seconds, with either normal or corrected 20/20 vision as self reported.

Of the twenty subjects, sixteen entered the experiment with a red advancing bias by which reds appeared closer than blues, three subjects had an opposing blue advancing bias, and one subject had a neutral bias by which neither red nor blue appeared closer.

APPARATUS

The experiment used JTIDS like symbols to represent the images on which the trial combinations were employed. The symbols and levels of hue and disparity were generated on a Silicon Graphics workstation using an IRIS 3130 graphics generator. The graphics generator had a 68020 microprocessor (16 MHz, 8 Mb memory) with 32 bit planes and 60 Hz non-interlacing capability. The symbols were then fed

into a graphic display controller which steps up synchronization from a sixty to one hundred and twenty hertz signal for the simultaneous display of two stereo images. The symbols were then presented on a high resolution, stereographic 3-D monitor, while the one hundred and twenty hertz signal was also sent to the electro-optical shuttering glasses. The glasses were liquid crystal shutters (LCSs) which were synchronized with the stereographic monitor in order to temporally alternate left- and right-eye stereoscopic images to the corresponding eye of the observer. (see Figure 4)

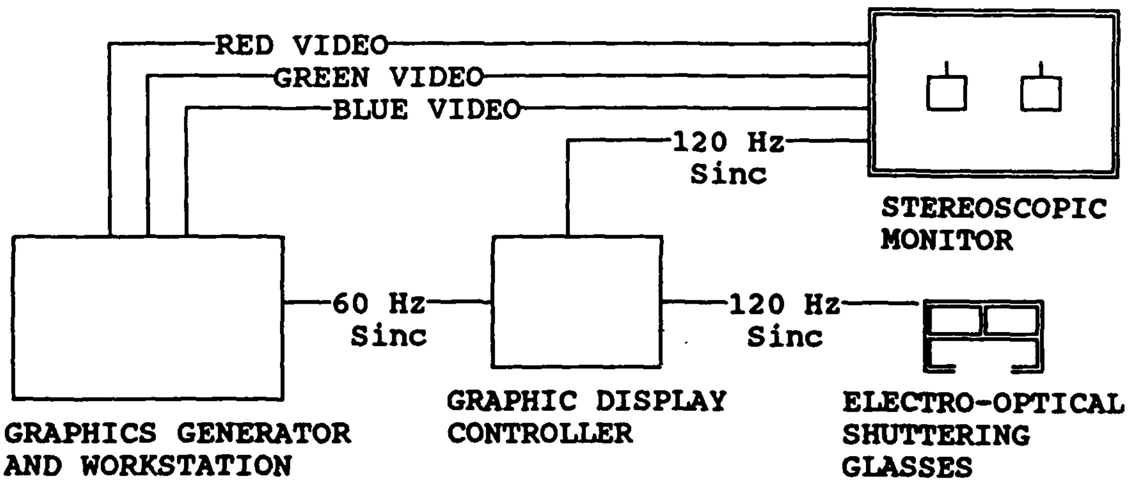

Fig. 4. Block diagram of apparatus.

The stereographic monitor was mounted in a generic fighter aircraft mockup, approximately the size of an F-15, called MAGIC. MAGIC is a design tool and test facility located in the Flight Dynamics Laboratory at Wright-Patterson AFB, Ohio, and is used for the test and evaluation

of advanced technologies for future aircraft.

In addition, the light level in the MAGIC facility was kept at a constant of thirty five Lux/meter during the experiment, and the sound level was approximately 58 dbA.

PROCEDURE

Each subject was first given a general information sheet discussing the nature of the experiment. After the subjects read the information sheet, each was given a static stereopsis and general color perception test to determine if they were qualified to participate in the experiment. Next, each subject was given a general briefing to familiarize them with the apparatus used in the experiment, explain experimental procedures, and allow them to ask any questions.

Each subject was then placed in the MAGIC cockpit (approximately 29 inches in front of a stereographic display), and instructed to wear the LCS glasses. When fitted with the glasses and ready, subjects were provided a practice session. The practice session was used to familiarize the subjects with the experimental presentation of the symbols, and determine the chromostereoscopic bias of the subjects (red-advancing, blue-advancing, or neither).

The practice sessions were divided into two parts. Part one consisted of four, unlimited duration, presentations of the symbol pairs at different disparity levels with no hue added, followed by the presentation of a

blue and red symbol with no induced disparity to determine the subject's bias. Part two of the practice session consisted of ten presentations of the symbol pairs as they would appear in actual data collection. Subjects were given as many practice sessions as they desired to become comfortable with the experimental presentation of the symbols.

Data collection began as subjects were presented with the first trial set of forty two JTIDS like symbols. The symbol pairs were presented in close proximity to one another on the center of the screen for a duration of 500 msec (this represents one trial). One of the JTIDS like symbols employed the various combinations of hue and disparity while the other symbol acted as the control symbol having the neutral hue of green and zero disparity.

After each trial presentation, subjects were be asked to indicate which symbol was closer (left or right), or if they where at the same depth. Subject responses were manually recorded by the experimenter and evaluated as either correct or incorrect as to the proper stereoscopic location of the symbols. To reduce fatigue, subjects were given short breaks between each trial set.

At the end of all 126 trials, each subject was given a questionnaire to determine personal bias, difficulty of the task, and general comments concerning the experiment.

IV. RESULTS

With a null hypothesis that hue has no effect on the perception of stereoscopic depth in a stereoscopic CRT, the results of an Analysis of Variance (ANOVA) of the data revealed three significant effects at the .05 level based on differences in the incidence of correct subject responses (accuracy). Accuracy was based on the subject's ability to correctly interpret the proper stereoscopic depth relationship of two objects which carried differing levels of hue (chromostereopsis effect) and disparity (stereopsis effect). The three effects included the level of hue, the level of disparity, and the interaction between hue and disparity. (see Table 1)

TABLE 1

RESULTS OF ANOVA

Source	DF	ANOVA SS	F Value	PR > F
Hue	5	8.18095238	2.99	0.0149
Disparity	6	214.26190476	28.07	0.0001
Hue*Disp.	30	83.85238095	4.83	0.0001

Once a significant difference in subject accuracy was determined using an ANOVA, a Finite Intersection Test (FIT)

was used to define where this significance existed within the levels of hue and disparity. FIT is a multivariate, simultaneous comparison test created by P.R. Krishnaiah of the University of Pittsburgh, 1980. FIT is analogous to univariate simultaneous comparison tests, e.g., Tukey or Sheffe, in that it allows the user to determine the level of the independent variable that significantly affects the dependent variable (Barry, Reising & Zenyuh, 1987).

Utilizing FIT at a .05 level of significance, the following significant differences in the incidence of correct subject responses (accuracy) were found. First, us:ng blue as a baseline of comparison, differences in subject accuracy across the range of hues used were evaluated. Comparing blue to each other level of hue, while remaining within equal levels of disparity, revealed the following. (see Table 2)

TABLE 2

SIGNIFICANT ACCURACY DIFFERENCES BETWEEN BLUE AND OTHER HUES WITHIN THE SAME DISPARITY LEVEL

Hues	at	Disparity Level
Blue and Cyan	at	0.00 arc minutes
Blue and Cyan	at	1.13 arc minutes
Blue and Green	at	-2.26 arc minutes
Blue and Yellow	at	-3.39 arc minutes
Blue and Yellow	at	-2.26 arc minutes
Blue and Yellow	at	0.00 arc minutes
Blue and Red	at	2.26 arc minutes

Second, when using green as the baseline of comparison,

significant differences between hues within the same level of disparity were found between green and blue at -2.26 arc minutes, and green and magenta at -2.26 arc minutes. Third, when FIT was used to compare subject accuracy between different levels of disparity, but within the same hue, significance differences were also found. (see Table 3) Fourth, each level of disparity was separately chosen as a base and compared for accuracy differences with all other levels of disparity. Again, several significant differences were found using FIT. (see Table 4)

TABLE 3

SIGNIFICANT ACCURACY DIFFERENCES BETWEEN DISPARITY LEVELS WITHIN THE SAME HUE

Disparity Levels	within	Hue
-2.26 & 2.26	within	Blue
-1.13 & 1.13	within	Blue
0.00 & 2.26	within	Blue
0.00 & 3.39	within	Blue
-2.26 & -1.13	within	Green
-2.26 & 0.00	within	Green
0.00 & 3.39	within	Green
1.13 & 2.26	within	Green
1.13 & 3.39	within	Yellow
-3.39 & -1.13	within	Magenta
-2.26 & 2.26	within	Magenta
0.00 & 2.26	within	Magenta
1.13 & 2.26	within	Magenta
1.13 & 3.39	within	Magenta
-3.39 & 2.26	within	Red
-2.26 & 3.39	within	Red
-1.13 & 3.39	within	Red

TABLE 4

SIGNIFICANT ACCURACY DIFFERENCES BETWEEN DISPARITY LEVELS

Base Level	-	Significantly Different Levels
-3.39	-	-1.13, 0.00, 1.13
-2.26	-	-1.13, 2.26, 3.39
-1.13	-	2.26, 3.39
0.00	-	2.26, 3.39
1.13	-	2.26
2.26	-	3.39

An interpretation of comments provided by subject questionnaires revealed several interesting statements. Five of theses statements were consistent across several subjects. These include:

1. Brighter colors often appeared closer.

2. The depth relationship of certain color combinations were harder to interpret than others. (Especially with blues and reds.)

3. Blues seemed to have the greatest effect on perception.

4. When both symbols were green, it was sometimes harder to perceive a depth difference.

5. When in doubt about depth differences, "same" was often chosen as the response.

In addition, the majority of subjects commented that the presentation time of 500 msec was sufficient to perceive the depth of the symbols, the experimental task of determining which symbol was closest was moderately

difficult, and that they put a good deal of effort into the task.

Finally, no difference was found in subject accuracy between male and female subjects.

V. DISCUSSION

Analysis of the data permits the following observations. Hue, disparity, and their interaction significantly affected the perception of artificial depth when viewing the stereoscopic CRT display. However, since the interaction of hue and disparity has a significant effect, the significance of each level of hue or disparity must be taken with caution since alone, each independent variable may not be significant at every level without this additional interaction effect.

It should be emphasized that the levels of disparity are a continuum. -3.39 arc minutes represents the closest point to the observer which is outside the screen plane, 0.00 arc minutes represents a point farther from the observer which is on the screen plane, and 3.39 arc minutes represents the farthest point away from the observer which is beyond the screen plane.

Second, disparity levels between -1.13 and 1.13 arc minutes contained generally lower subject response accuracy then all other levels of disparity. This is believed to be a result of the greater difficulty of discriminating smaller disparity differences. Also, the zero level of disparity showed generally higher accuracy then either the -1.13 or

1.13 levels. This may have risen from an initial subject tendency to respond that both symbols were at the same distance.

Third, as disparity levels approached the extremes (-3.39 and 3.39), the effect of hue began to decrease. It is believed that with higher disparity levels than the ones used in this research, the contribution of hue to depth perception would be diminished.

Fourth, if we look at the affect of blue along the continuum of disparity, it is obvious that blue affects the perception of depth in accordance with chromostereoscopic theory in that the accuracy of perceiving closer objects was decreased due to a blue chromostereoscopic effect and the accuracy of more distant objects increased due to the same blue effect. (see Figure 5) For example, blue portrayed a sense of depth in the opposite direction of negative stereoscopic disparity, thus decreasing accuracy. Yet, with positive stereoscopic disparities, blue enhanced the sense of depth and accuracy increased by a significant amount. In short, blue aided the positive disparities and countered the negative ones.

Fifth, green can be considered a neutral color since it is near the center of the hue frequency spectrum. As a result it would be expected to have no affect on disparity and would be symmetrical on both sides of the zero disparity level. Examination of Figure 6 verifies this by green's

symmetrical "W" shape.

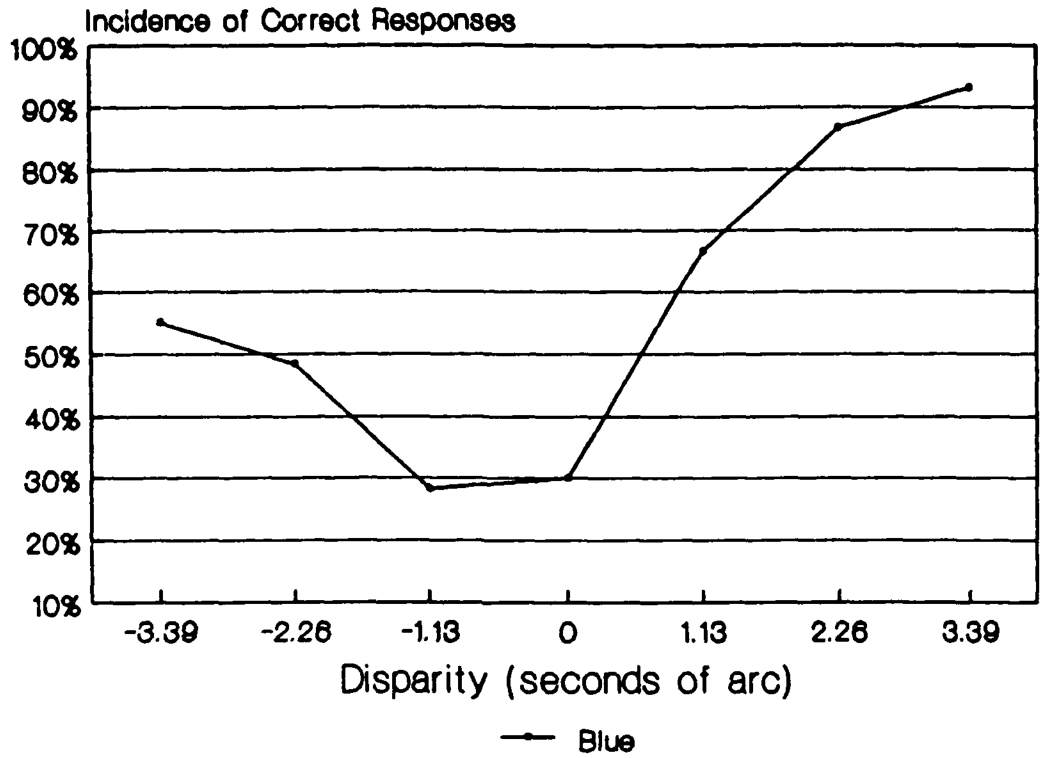

Fig. 5. The interaction of blue and disparity.

Sixth, accuracy associated with red was significantly less than that of blue while using positive disparities. As expected, this demonstrates how red hues portray depth in the opposite direction of blues. Thus, accuracy for red was higher than blue while using negative stereoscopic disparities, and lower than blue while using positive disparities. (see Figure 7) The opposite depths portrayed by blues and reds are also evident in the crossing of the blue and red plots as they go over the zero disparity line

in Figure 7.

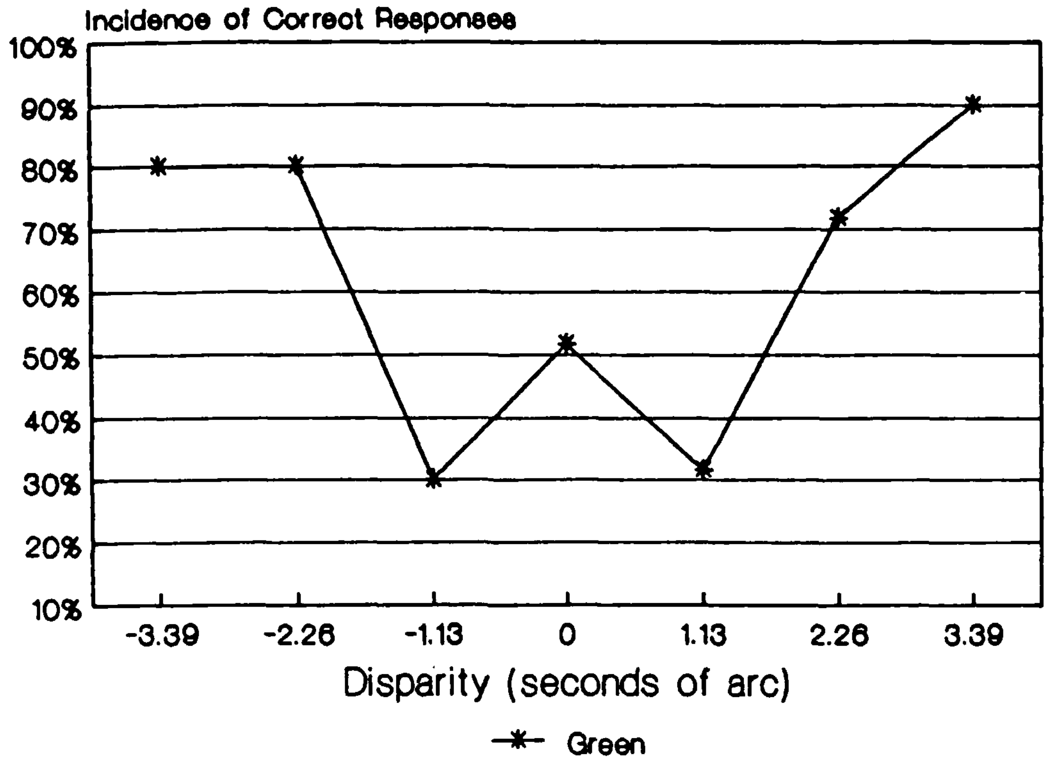

Fig. 6. Green and disparity interaction

This illustrates the need for caution when using hues on extreme ends of the color spectrum to represent symbols in close proximity on a stereoscopic display.

An unexpected result of the study was the lack of significant differences between accuracy associated with red and blue while using negative disparities, and that the accuracy associated with red was not significantly different at equal but opposite levels of disparity as blue and magenta were. One or a combination of three hypothesis may explain these unexpected results. First, these results may

be due to subject error. Second, the chromostereoscopic effect of blue may be stronger than that of red, while noting that most subjects had a red advancing bias. Third, unknown factors associated with presenting objects out of the screen (negative disparity) had some uncontrolled affect on chromostereopsis.

Seventh, cyan was shown to have no significant effect on depth perception. In Figure 8 this is clear by noting that except for the -1.13 point, cyan is very similar to the neutral green "W".

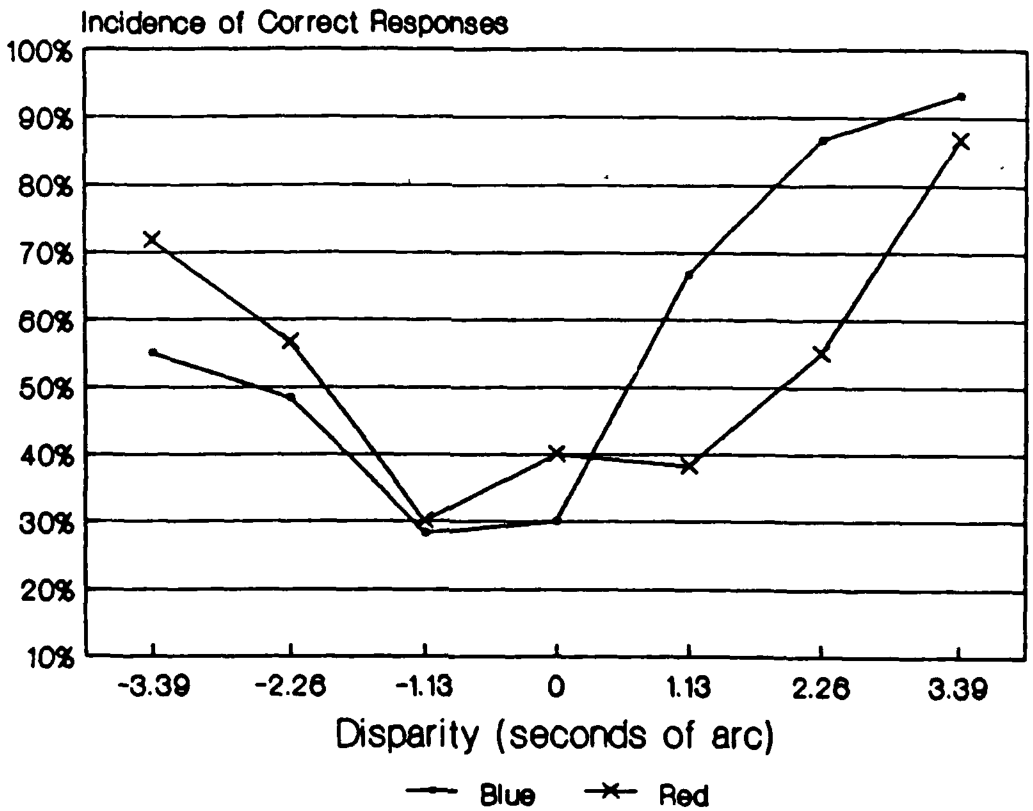

Fig. 7. Red, Blue, and disparity interactions

The crossing of cyan and blue over the zero point may be

explained in that cyan can be considered a much brighter hue, and thus imitate actions of red because brighter hues are generally perceived closer than darker ones.

Eighth, yellow is very similar to the neutral green "W" as with cyan. (see Figure 9) The significance found in yellow is similar to that of cyan and more then likely due to disparity interactions since there was no significant difference in yellow across the zero point of disparity.

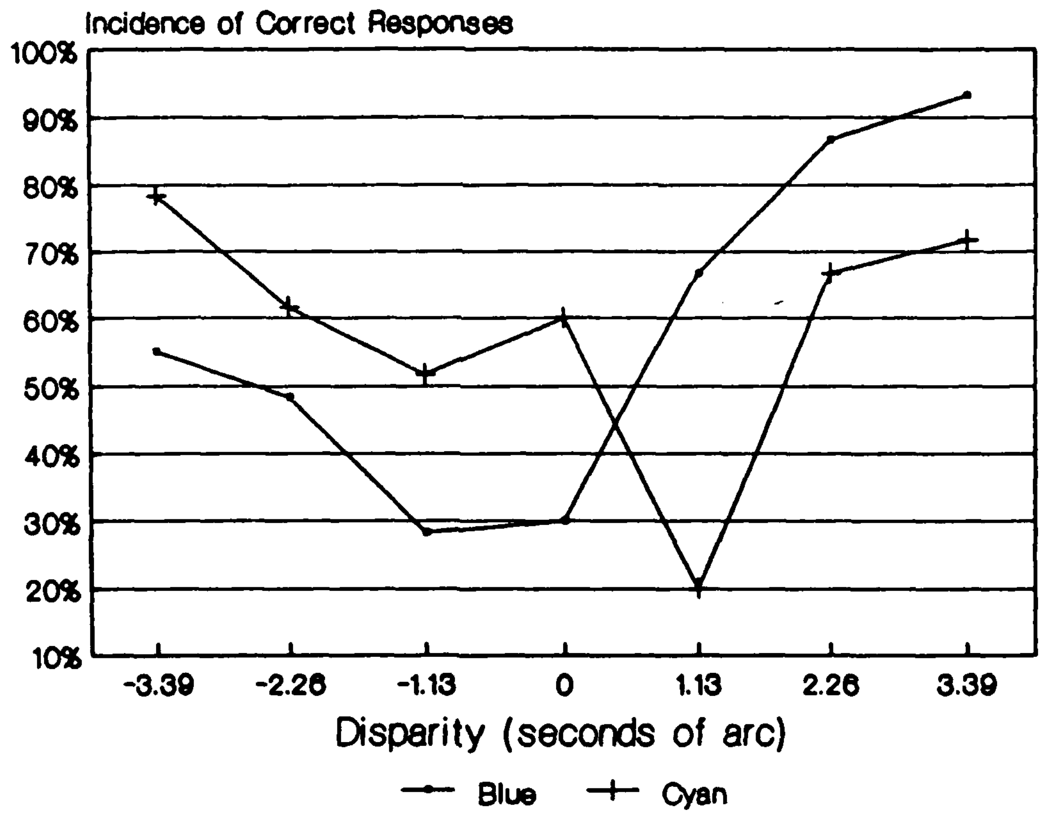

Fig. 8. Cyan, blue, and disparity interactions.

The higher accuracy related to yellow over red in the negative disparity levels is more then likely due to its brighter appearance.

Finally, as would be expected, the results related to magenta are similar to red, yet slightly different when crossing the zero disparity point. Unlike red, the effect of magenta proved to be significant in equal opposite levels of disparity.

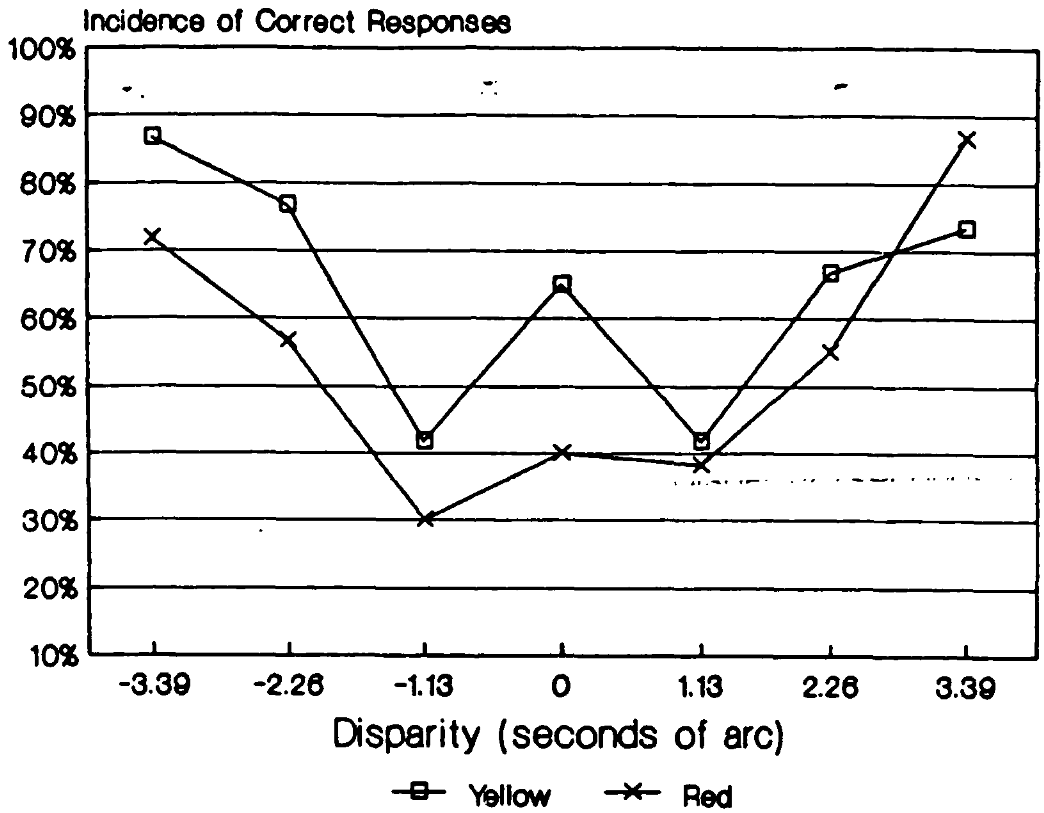

Fig. 9. Yellow, red, and disparity interactions

This indicates that its significance is more then likely a main effect as with blue. Reason would suggest that if magenta is significant on equal opposite levels of disparity, then red should be also, yet in this research red was not. This cannot be explained within the context of this experiment and should be an area for further research.

(see Figure 10)

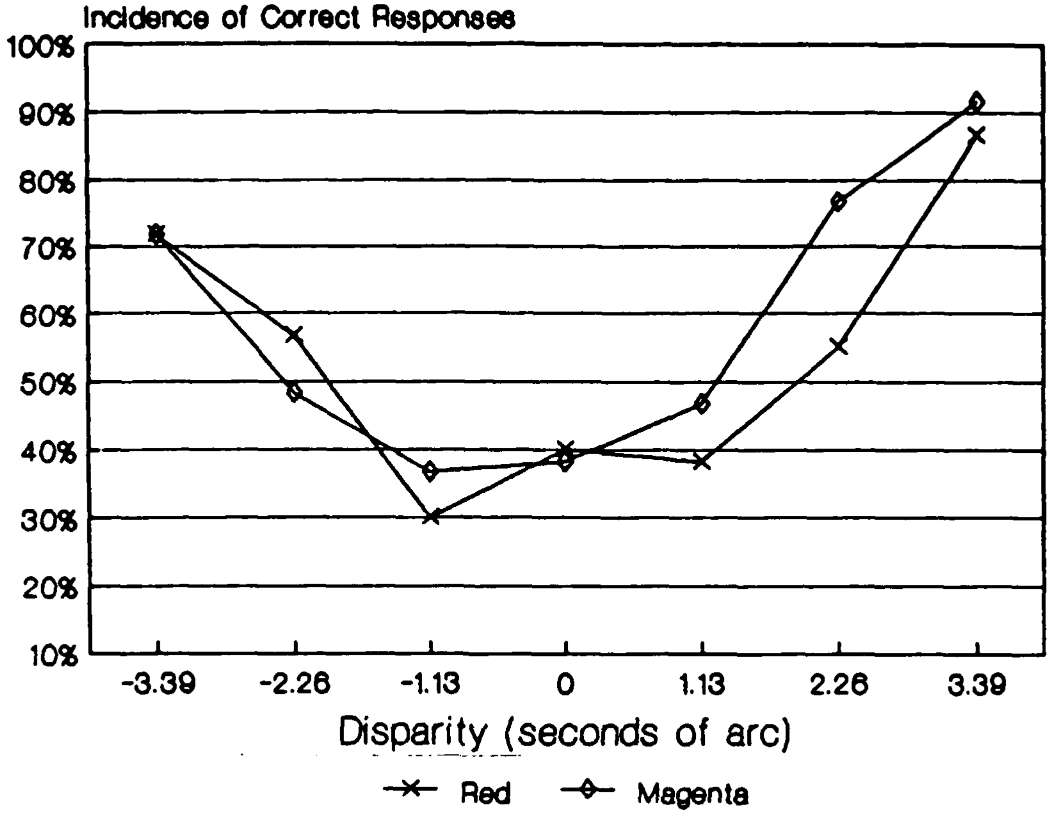

Fig. 10. Magenta, red, and disparity interactions.

VI. CONCLUSION

This research demonstrates that chromostereopsis can significantly affect the stereoscopic perception of depth on a stereoscopic display when disparity levels are relatively small. It is suggested that caution be used by the stereoscopic 3-D display format designer when choosing hues to represent 3-D images located in close proximity. This is especially true when considering the use of hues near either end of the frequency spectrum.

If such colors must be used in close proximity, the designer should use them in a consistent manner so as to reduce confusion of false depth resulting from unwanted chromostereopsis, or consistently adjust stereoscopic disparity levels used with such hues to nullify unwanted chromostereopsis.

It is also suggested that adjacent symbols with stereoscopic disparity differences between them of 3.39 arc minutes or less avoid the use of colors on extreme ends of the frequency spectrum unless they are intended to consistently enhance or negate depth perception represented by stereoscopic disparity. Likewise, due to the ineffective nature of chromostereopsis when coupled with large differences in stereoscopic disparity, it is believed that

disparity differences between adjacent symbols greater than 3.39 arc minutes will not be significantly affected by hue.

Finally, when designing 3-D display formats that use various hues, chromostereopsis cannot be considered the only factor of hue that may effect the perception of stereoscopic depth. This research suggests that variables other than hue, e.g., hue brightness, also influence depth perception performance.

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APPENDIX A

SPECTRA RADIOMETER READINGS OF HUES

The following three pages contain spectra radiometer readings of each hue as it appeared on the stereoscopic screen. Readings were taken via a Photo Research Spectrascan with the stereoscopic monitor positioned in the M.A.G.I.C. cockpit under the same conditions of the experiment, except that all room lights where extinguished to prevent improper spectrascan readings. Multiple peaks in the spectra radiometer output represent combinations of red, green, and blue phosphors used to create a specific hue.

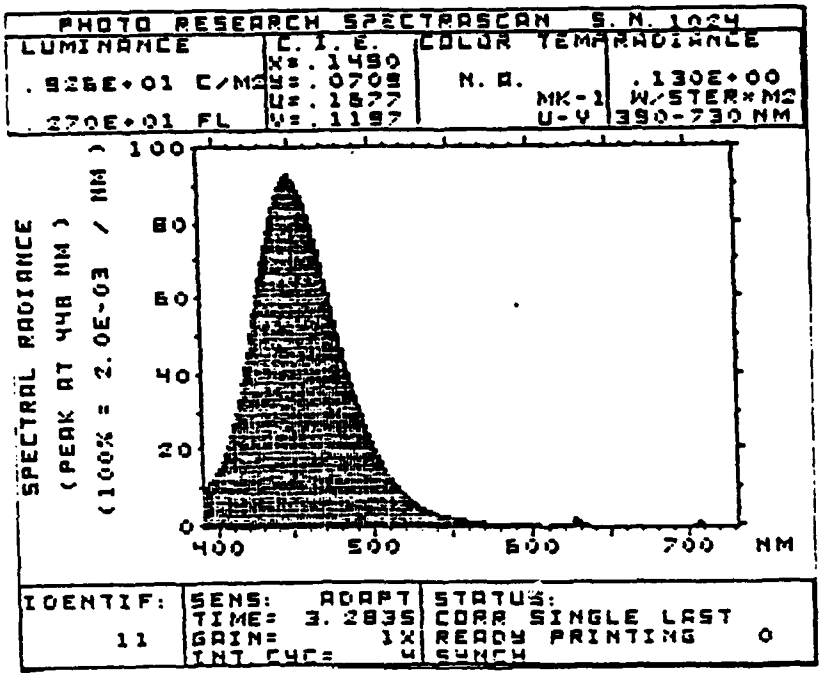

Fig. 11. *Spectra Radiometer reading of blue.*

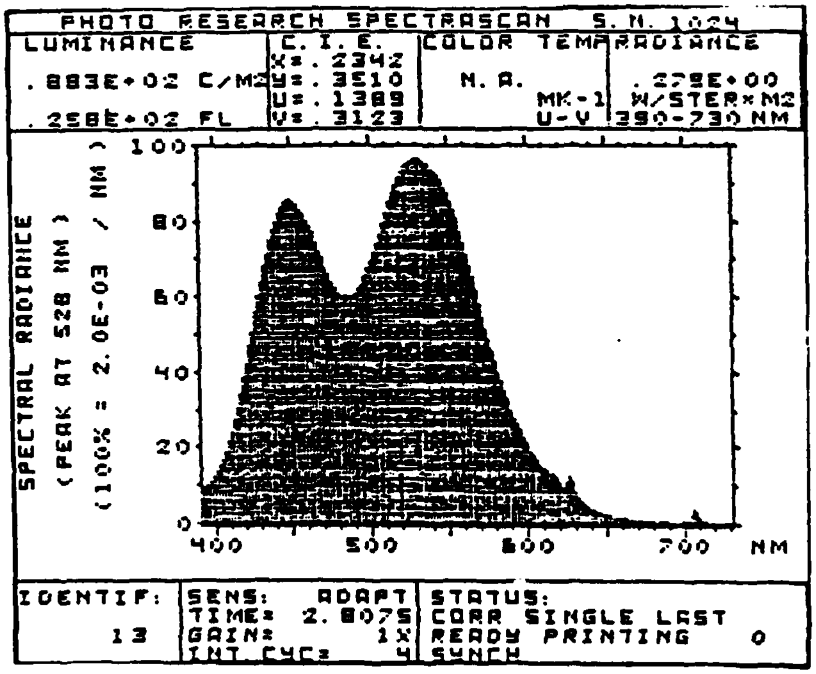

Fig. 12. Spectra Radiometer reading of cyan.

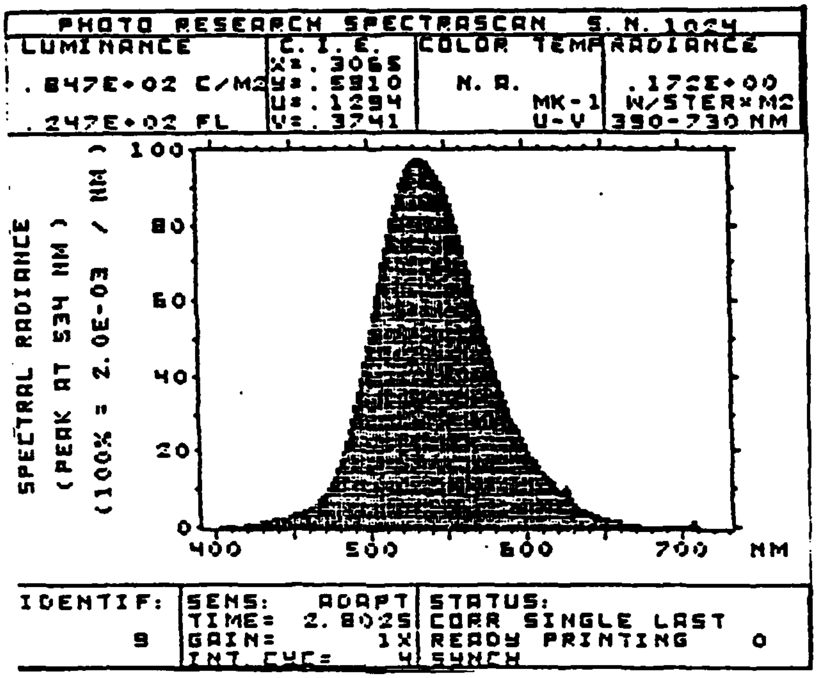

Fig. 13. Spectra Radiometer reading of green.

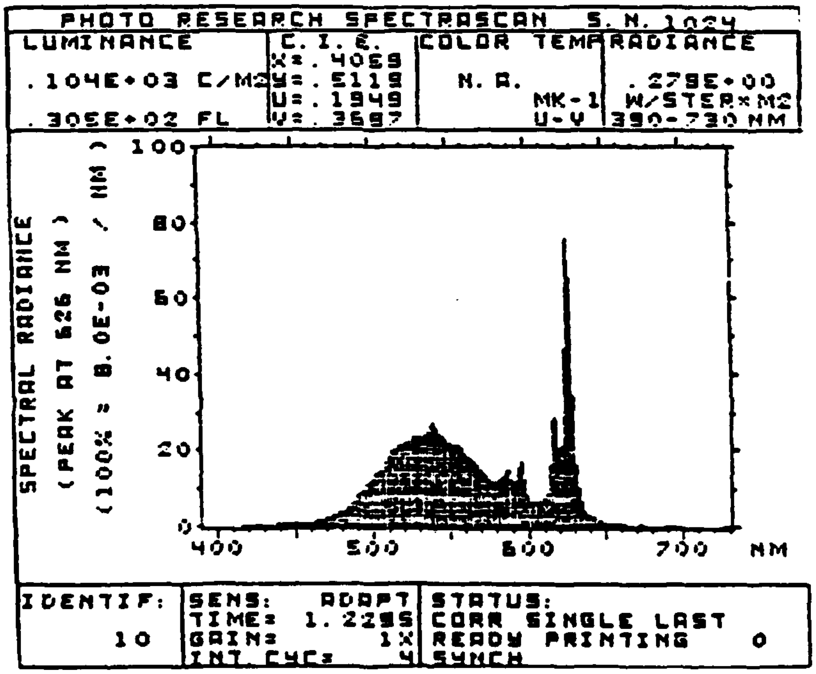

Fig. 14. Spectra Radiometer reading of yellow.

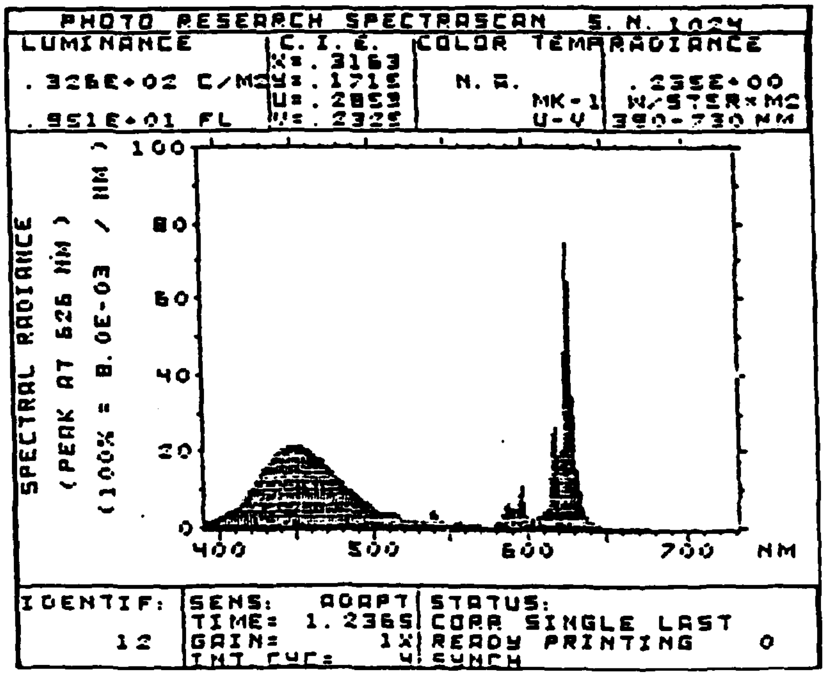

Fig. 15. Spectra Radiometer reading of magenta.

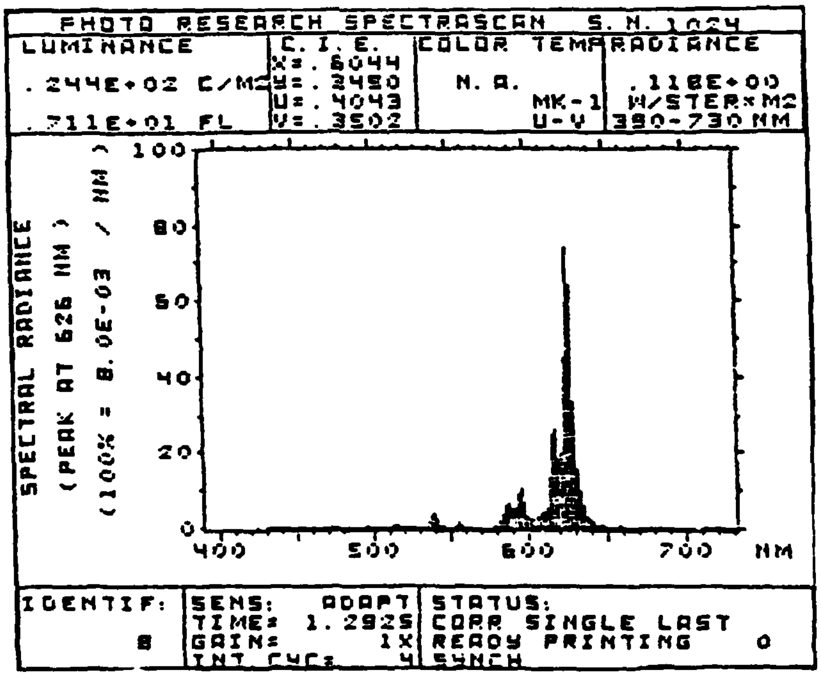

Fig. 16. Spectra Radiometer reading of red.

APPENDIX B

DATA ANALYSIS PREPARATION PROGRAMS

The following programs where written by the author for the purpose of taking the hand collected data from subject responses and preparing it for data analysis. The data analysis key should be used by the reader in conjunction with each program for a better understanding of each program's functions.

DATA ANALYSIS KEY

SEX	BIAS	HUE (ADV. COLOR)	DISPARITY (ARC MIN)
1 = MALE	1 = BLUE	1 = BLUE	1 = -3.39
0 = FEMALE	2 = RED	2 = CYAN	2 = -2.26
	3 = NONE	3 = GREEN	3 = -1.13
		4 = YELLOW	4 = 0
		5 = RED	5 = 1.13
		6 = MAGENTA	6 = 2.26
			7 = 3.39

DIRECTION OF RESPONSE (RESPONSE ACCORDING TO COLOR BIAS)
1 = WITH BIAS
2 = AGAINST BIAS
3 = N/A

"JIMTHS" was the main program used to used to transform raw data into understandable information. It ordered the data, determined the scores of each subject, the direction of responses, and put the data in a format necessary for later data analysis.

```
Program JIMTHS;

VAR filein, fileout, matrix: text;
    bias, corr, resp, sex, hue, dum1,
    dum2, dum3, dum4: char;
    score:real;
    s, r, sub, disp, dir, biasn, huen,
    sexn: integer;

procedure setscore;
  begin
    if (resp = corr) then score := 1.0
    else score := 0.0;
  end;

procedure direction;
  begin
    if bias = 'B' then      (* Blue is Advancing Color *)
      begin
          if (hue in ['B','C']) and (disp in [1,2,3]) and
          (resp = corr) then
            dir := 1
          else if (hue in ['B','C']) and (disp in [5,6,7])
                  and (resp <> corr) then
            dir := 1
          else if (hue in ['B','C']) and (disp in [1,2,3])
                  and (resp <> corr) then
            dir := 2
          else if (hue in ['B','C']) and (disp in [5,6,7])
                  and (resp = corr) then
            dir := 2
          else if (hue in ['Y','R','M']) and (disp in
                  [1,2,3]) and (resp = corr) then
            dir := 2
          else if (hue in ['Y','R','M']) and (disp in
                  [5,6,7]) and (resp <> corr) then
            dir := 2
          else if (hue in ['Y','R','M']) and (disp in
                  [1,2,3]) and (resp <> corr) then
```

```
            dir := 1
          else if (hue in ['Y','R','M']) and (disp in
                  [5,6,7]) and (resp = corr) then
            dir := 1
          else dir := 3;
      end;
    if bias = 'R' then      (* Red is Advancing Color (Most
                              Common) *)
      begin
          if (hue in ['Y','R','M']) and (disp in [1,2,3])
             and (resp = corr) then
            dir := 1
          else if (hue in ['Y','R','M']) and (disp in
                  [5,6,7]) and (resp <> corr) then
            dir := 1
          else if (hue in ['Y','R','M']) and (disp in
                  [1,2,3]) and (resp <> corr) then
            dir := 2
          else if (hue in ['Y','R','M']) and (disp in
                  [5,6,7]) and (resp = corr) then
            dir := 2
          else if (hue in ['B','C']) and (disp in [1,2,3])
                  and (resp = corr) then
            dir := 2
          else if (hue in ['B','C']) and (disp in [5,6,7])
                  and (resp <> corr) then
            dir := 2
          else if (hue in ['B','C']) and (disp in [1,2,3])
                  and (resp <> corr) then
            dir := 1
          else if (hue in ['B','C']) and (disp in [5,6,7])
                  and (resp = corr) then
            dir := 1
          else dir := 3;
      end;
    if bias = 'N' then    (* No Bias *)
      dir := 3;
  end; (* direction *)

Procedure change;
  begin
    case hue of
      'B': huen := 1;
      'C': huen := 2;
      'G': huen := 3;
      'Y': huen := 4;
      'R': huen := 5;
      'M': huen := 6;
    end; (* case hue *)
    case bias of
      'B': biasn := 1;
      'R': biasn := 2;
```

```
      'N': biasn := 3;
    end; (* case bias *)
    case sex of
      'M': sexn := 1;
      'F': sexn := 0;
    end; (* case sex *)
  end; (* change *)

BEGIN
  assign (filein, 'c:jimths.dat');
  assign (fileout, 'c:jimspss.dat');
  assign (matrix, 'c:\turbo\matrix.dat');
  reset (filein);
  rewrite (fileout);
  reset (matrix);

  For s := 1 to 20 do
    begin
      readln (filein, sub, dum1, sex, dum2, bias);
      For r := 1 to 126 do
        begin
          readln (filein, resp);
          readln (matrix, hue, dum3, disp, dum4, corr);
          setscore;
          direction;
          change;
          writeln (fileout, sub:2, sexn:2, biasn:2, huen:2,
                  disp:2,' ', score:1:1, dir:2);
        end; (* For r *)
      reset (matrix);
    end; (* For s *)

  close (filein);
  close (fileout);
  close (matrix);
END. (* MAIN *)
```

"SUMTHS" simply summed up the total score of each subject for each condition. This was not needed for data analysis, but aided in the interpretation and presentation of results.

```
Program sumths;

var  filein, fileout: text;
     sub, sex, bias, disp, hue, dir, s, n: integer;
     score, b1, b2, b3, b4, b5, b6, b7, c1,
     c2, c3, c4, c5, c6, c7, g1, g2, g3, g4,
     g5, g6, g7, y1, y2, y3, y4, y5, y6, y7,
     r1, r2, r3, r4, r5, r6, r7, m1, m2, m3,
```

```
    m4, m5, m6, m7: real;

Procedure initialize;
  begin
    b1 := 0.00;
    b2 := 0.00;
    b3 := 0.00;
    b4 := 0.00;
    b5 := 0.00;
    b6 := 0.00;
    b7 := 0.00;
    c1 := 0.00;
    c2 := 0.00;
    c3 := 0.00;
    c4 := 0.00;
    c5 := 0.00;
    c6 := 0.00;
    c7 := 0.00;
    g1 := 0.00;
    g2 := 0.00;
    g3 := 0.00;
    g4 := 0.00;
    g5 := 0.00;
    g6 := 0.00;
    g7 := 0.00;
    y1 := 0.00;
    y2 := 0.00;
    y3 := 0.00;
    y4 := 0.00;
    y5 := 0.00;
    y6 := 0.00;
    y7 := 0.00;
    r1 := 0.00;
    r2 := 0.00;
    r3 := 0.00;
    r4 := 0.00;
    r5 := 0.00;
    r6 := 0.00;
    r7 := 0.00;
    m1 := 0.00;
    m2 := 0.00;
    m3 := 0.00;
    m4 := 0.00;
    m5 := 0.00;
    m6 := 0.00;
    m7 := 0.00;
  end;

 BEGIN
   assign (filein, 'c:jimspss.dat');
   assign (fileout, 'c:jimspss.rdy');
   reset (filein);
```

```
  rewrite (fileout);
  For s := 1 to 20 do
   begin
    initialize;
    For n := 1 to 126 do
     begin
      readln (filein, sub, sex, bias, hue, disp, score,
dir);
      case hue of
       1:begin
        if disp = 1 then b1 := b1 + score
        else if disp = 2 then b2 := b2 + score
        else if disp = 3 then b3 := b3 + score
        else if disp = 4 then b4 := b4 + score
        else if disp = 5 then b5 := b5 + score
        else if disp = 6 then b6 := b6 + score
        else if disp = 7 then b7 := b7 + score
       end;
      2:begin
       if disp = 1 then c1 := c1 + score
       else if disp = 2 then c2 := c2 + score
       else if disp = 3 then c3 := c3 + score
       else if disp = 4 then c4 := c4 + score
       else if disp = 5 then c5 := c5 + score
       else if disp = 6 then c6 := c6 + score
       else if disp = 7 then c7 := c7 + score
      end;
     3:begin
      if disp = 1 then g1 := g1 + score
      else if disp = 2 then g2 := g2 + score
      else if disp = 3 then g3 := g3 + score
      else if disp = 4 then g4 := g4 + score
      else if disp = 5 then g5 := g5 + score
      else if disp = 6 then g6 := g6 + score
      else if disp = 7 then g7 := g7 + score
     end;
    4:begin
      if disp = 1 then y1 := y1 + score
      else if disp = 2 then y2 := y2 + score
      else if disp = 3 then y3 := y3 + score
      else if disp = 4 then y4 := y4 + score
      else if disp = 5 then y5 := y5 + score
      else if disp = 6 then y6 := y6 + score
      else if disp = 7 then y7 := y7 + score
     end;
    5:begin
      if disp = 1 then r1 := r1 + score
      else if disp = 2 then r2 := r2 + score
      else if disp = 3 then r3 := r3 + score
      else if disp = 4 then r4 := r4 + score
      else if disp = 5 then r5 := r5 + score
      else if disp = 6 then r6 := r6 + score
```

```
      else if disp = 7 then r7 := r7 + score
     end;
    6:begin
      if disp = 1 then m1 := m1 + score
      else if disp = 2 then m2 := m2 + score
      else if disp = 3 then m3 := m3 + score
      else if disp = 4 then m4 := m4 + score
      else if disp = 5 then m5 := m5 + score
      else if disp = 6 then m6 := m6 + score
      else if disp = 7 then m7 := m7 + score
     end;
    end; (* case hue *)
   end; (* for n *)
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','1',' ','1','
            ',b1:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','1',' ','2','
            ',b2:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','1',' ','3','
            ',b3:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','1',' ','4','
            ',b4:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','1',' ','5','
            ',b5:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','1',' ','6','
            ',b6:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','1',' ','7','
            ',b7:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','2',' ','1','
            ',c1:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','2',' ','2','
            ',c2:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','2',' ','3','
            ',c3:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','2',' ','4','
            ',c4:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','2',' ','5','
            ',c5:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','2',' ','6','
            ',c6:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','2',' ','7','
            ',c7:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','3',' ','1','
            ',g1:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','3',' ','2','
            ',g2:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','3',' ','3','
            ',g3:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','3',' ','4','
            ',g4:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','3',' ','5','
            ',g5:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','3',' ','6','
```

```
                ',g6:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','3',' ','7','
                ',g7:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','4',' ','1','
                ',y1:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','4',' ','2','
                ',y2:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','4',' ','3','
                ',y3:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','4',' ','4','
                ',y4:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','4',' ','5','
                ',y5:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','4',' ','6','
                ',y6:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','4',' ','7','
                ',y7:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','5',' ','1','
                ',r1:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','5',' ','2','
                ',r2:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','5',' ','3','
                ',r3:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','5',' ','4','
                ',r4:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','5',' ','5','
                ',r5:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','5',' ','6','
                ',r6:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','5',' ','7','
                ',r7:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','6',' ','1','
                ',m1:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','6',' ','2','
                ',m2:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','6',' ','3','
                ',m3:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','6',' ','4','
                ',m4:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','6',' ','5','
                ',m5:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','6',' ','6','
                ',m6:3:2);
  writeln (fileout, sub:2,' ',sex,' ',bias,' ','6',' ','7','
                ',m7:3:2);
 end; (* for s *)
 close (filein);
 close (fileout);
END. (* MAIN *)
```

APPENDIX C

SAS ANOVA OUTPUT

The following pages are a reproduction of the results associated with a SAS analysis of variance (ANOVA) performed on the Wright State University IBM main frame.

```
SAS(R) LOG OS SAS 5.16    MVS/XA JOB FAJIM1 STEP SAS5
14:49 WEDNESDAY, JUNE 29, 1988


DATA JIMTHS1;
INPUT SUB SEX BIAS HUE DISP SCORE;
CARDS;
   NOTE:DATA SET WORK.JIMTHS1 HAS 840 OBSERVATIONS
        AND 6 VARIABLES. 885 OES/TRK.
;
PROC ANOVA;
CLASSES SUB HUE DISP;
MODEL SCORE = SUB HUE DISP HUE*DISP SUB*HUE SUB*DISP
   SUB*HUE*DISP;
TEST H = HUE        E = SUB*HUE;
TEST H = DISP       E = SUB*DISP;
TEST H = HUE*DISP   E = SUB*HUE*DISP;
TITLE 'JIM MCCLAIN   THESIS DATA ANALYSIS OUTPUT';
```

JIM MCCLAIN THESIS DATA ANALYSIS OUTPUT
ANALYSIS OF VARIANCE PROCEDURE
CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
SUB	20	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
HUE	6	1 2 3 4 5 6
DISP	7	1 2 3 4 5 6 7

NUMBER OF OBSERVATIONS IN DATA SET = 840

DEPENDENT VARIABLE: SCORE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	839	1011.69523810	1.20583461	.
ERROR	0	0.00000000	0.00000000	
CORRECTED TOTAL	839	1011.69523810		

PR > F	R-SQUARE	C.V.	ROOT MSE	SCORE MEAN
.	1.000000	0.0000	0.000000	1.78095238

SOURCE	DF	ANOVA SS	F VALUE	PR > F
SUB	19	178.74285714	.	.
HUE	5	8.18095238	.	.
DISP	6	214.26190476	.	.
HUE*DISP	30	83.85238095	.	.
SUB*HUE	95	51.91428571	.	.
SUB*DISP	114	145.02380952	.	.
SUB*HUE*DISP	570	329.71904762	.	.

TESTS OF HYPOTHESIS USING THE ANOVA MS FOR SUB*HUE AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
HUE	5	8.18095238	2.99	0.0149

TESTS OF HYPOTHESIS USING THE ANOVA MS FOR SUB*DISP AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
DISP	6	214.26190476	28.07	0.0001

TESTS OF HYPOTHESIS USING THE ANOVA MS FOR SUB*HUE*DISP AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
HUE*DISP	30	83.85238095	4.83	0.0001

APPENDIX D

TEST MATRIX AND ASSOCIATED KEYS

The following three pages include the matrix table key, a list of the independent variables and their levels, the trial combinations key, the three randomized trial sets used, and the matrix table.

Matrix Table Key

Matrix	=	Indicator for Software
Subject	=	Subject Number
Set	=	One of Three Trial Sets

Independent Variables and Levels

I.V. #1 (HUE)	I.V. #2 (DISPARITY)
B = Blue	1 = -3.39
C = Cyan	2 = -2.26
G = Green	3 = -1.13
Y = Yellow	4 = 0
R = Red	5 = 1.13
M = Magenta	6 = 2.26
	7 = 3.39

Trial Combinations

Combo	Hue	Disparity	Combo	Hue	Disparity
1	B	1	22	Y	1
2	B	2	23	Y	2
3	B	3	24	Y	3
4	B	4	25	Y	4
5	B	5	26	Y	5
6	B	6	27	Y	6
7	B	7	28	Y	7
8	C	1	29	R	1
9	C	2	30	R	2
10	C	3	31	R	3
11	C	4	32	R	4
12	C	5	33	R	5
13	C	6	34	R	6
14	C	7	35	R	7
15	G	1	36	M	1
16	G	2	37	M	2
17	G	3	38	M	3
18	G	4	39	M	4
19	G	5	40	M	5
20	G	6	41	M	6
21	G	7	42	M	7

Randomized Trial Sets

L/R = L :Left symbol contains Trial combination.
R :Right symbol contains Trial combination.

Trial	Set #1	Set #2	Set 3#
1	21 R	30 L	34 R
2	17 R	24 R	13 R
3	8 R	4 R	7 L
4	28 R	17 L	12 R
5	36 R	39 R	16 R
6	5 R	20 L	4 L
7	25 L	23 L	8 L
8	1 R	40 L	14 R
9	22 L	31 R	37 L
10	39 L	7 R	9 R
11	26 L	16 R	22 R
12	12 R	21 L	5 L
13	6 R	9 L	40 R
14	3 L	11 L	15 R
15	37 R	27 R	30 R
16	14 R	2 R	1 R
17	35 R	3 R	17 L
18	15 R	5 L	41 R
19	2 L	37 L	19 R
20	31 L	26 L	24 L
21	32 L	22 R	6 L
22	30 L	8 R	33 L
23	41 L	29 R	11 R
24	11 L	35 R	38 L
25	27 R	38 L	10 L
26	38 L	33 R	18 R
27	7 R	6 R	3 R
28	16 L	28 R	23 R
29	19 R	41 R	42 L
30	13 R	1 R	2 R
31	29 L	12 R	39 R
32	40 R	25 L	21 L
33	18 L	34 L	20 L
34	33 R	10 L	29 L
35	10 L	15 L	36 L
36	20 R	18 L	25 R
37	4 R	32 L	32 L
38	9 L	19 L	28 L
39	42 R	36 L	26 R
40	24 R	13 L	35 L
41	23 R	42 L	31 L
42	34 R	14 L	27 R

Matrix Table

Matrix	Subject	Set	Matrix	Subject	Set
1	1	1	31	11	2
2	1	2	32	11	1
3	1	3	33	11	3
4	2	2	34	12	1
5	2	3	35	12	3
6	2	1	36	12	2
7	3	3	37	13	1
8	3	1	38	13	2
9	3	2	39	13	3
10	4	3	40	14	2
11	4	2	41	14	3
12	4	1	42	14	1
13	5	2	43	15	3
14	5	1	44	15	1
15	5	3	45	15	2
16	6	1	46	16	3
17	6	3	47	16	2
18	6	2	48	16	1
19	7	1	49	17	2
20	7	2	50	17	1
21	7	3	51	17	3
22	8	2	52	18	1
23	8	3	53	18	3
24	8	1	54	18	2
25	9	3	55	19	1
26	9	1	56	19	2
27	9	2	57	19	3
28	10	3	58	20	2
29	10	2	59	20	3
30	10	1	60	20	1

APPENDIX E

DATA COLLECTION SHEET

The following page is a replica of the data collection sheet used in this research. The data from this sheet was input into programs that prepared the data for a final ANOVA.

DATA COLLECTION SHEET

Subject #____ Sex____ Date_______ Time_______
Stereo Vision______ Color Vision_______
Advancing Color_______ # of Practice Sessions____
Marix #'s ___ ___ ___ Order of Sets ___ ___ ___

	Set# 1 ( )		Set# 2 ( )		Set# 3 ( )	
1	L	____	L	____	R	____
2	R	____	R	____	L	____
3	R	____	S	____	R	____
4	L	____	L	____	L	____
5	R	____	S	____	R	____
6	L	____	R	____	S	____
7	S	____	L	____	L	____
8	R	____	R	____	L	____
9	L	____	R	____	L	____
10	S	____	L	____	R	____
11	R	____	R	____	R	____
12	L	____	R	____	R	____
13	L	____	L	____	L	____
14	L	____	S	____	R	____
15	R	____	L	____	R	____
16	L	____	R	____	R	____
17	L	____	R	____	L	____
18	R	____	R	____	L	____
19	L	____	L	____	L	____
20	L	____	R	____	L	____
21	S	____	R	____	R	____
22	L	____	R	____	L	____
23	R	____	R	____	S	____
24	S	____	L	____	L	____
25	L	____	L	____	L	____
26	L	____	L	____	S	____
27	L	____	L	____	R	____
28	L	____	L	____	R	____
29	L	____	L	____	R	____
30	L	____	R	____	R	____
31	L	____	L	____	S	____
32	L	____	S	____	R	____
33	S	____	R	____	R	____
34	L	____	L	____	L	____
35	L	____	L	____	L	____
36	L	____	S	____	S	____
37	S	____	S	____	S	____
38	L	____	R	____	R	____
39	L	____	L	____	L	____
40	R	____	R	____	R	____
41	R	____	R	____	L	____
42	L	____	R	____	L	____

APPENDIX F

TEST PROCEDURE CHECKLIST

The following is a replication of the procedural checklist used in experimentation.

Apparatus:

1) MAGIC Cockpit
2) Stereoscopic CRT
3) Passive Polarized Glasses
4) Static Stereo Test
5) Pseudo-Isochromatic Test

Procedure:

1) Give subject information sheet and allow to read.
2) Brief purpose of experiment: to test 3-D format development.
3) Explain apparatus.
4) Static Stereo screening.
5) Isochromatic screening.
6) Place subject in MAGIC seat.
7) Give subject LCD shutter glasses.
8) Call up practice session on computer.
9) Explain symbols and how they will be displayed. This should include: attention signal, small delay, 500ms presentation of symbols, subject response of Left/Right/Same, three sets of 42 combinations with different colors, and always one symbol green.
10) Practice identifying disparity. (Advancing Side on the first four practice presentations: L,R,L,R)
11) Evaluate chromatic bias and note on data sheet.
12) Ask subject if they want another practice session.
13) Proceed to first, second, and third matrix with rest period in between is subject desires.

APPENDIX G

RESEARCH INFORMATION SHEET

The following sheet of information was given to each subject before they participated in the experiment.

Research Information Sheet
(for Subjects)

1) The research you are about to participate in is voluntary and deals with the development of three dimensional (3-D) display formats. It is non-intrusive research that posses no risk to you as a subject. The actual experiment will take approximately one hour in which you will be asked to respond to your perception of different combinations of adjacent symbols presented on a 3-D display.
2) The apparatus and specific procedures used in this research will be explained to you by the investigator after you have read this sheet. Feel free to ask any questions at that time.
3) If you have: non-standard color vision, a lack of stereoscopic (binocular) vision, or less than 20/20 corrected vision; your participation may be terminated by the investigator without your consent. (These are critical factors for good test results in this research.)
4) If at any time you wish to terminate your participation in this research, simply inform the investigator and you will be excused without repercussion. However, please realize that termination once the experiment has begun will greatly delay the completion of this research so please notify the investigator as quickly as possible if you wish to terminate your participation.
5) All data collected from your responses will not be used in any way that will violate your privacy.
6) A debriefing will be given to you after the experiment that will explain the purpose of this research and answer any questions you may have.
7) If you desire the final results of the research or have any additional questions after you participation. Feel free to contact Lt James McClain at (256-2603) or Dr. Anthony Cacioppo at (873-3328).

APPENDIX H

POST-EXPERIMENT QUESTIONNAIRE

The following is a replication of the questionnaire given to each subject upon completion of the thesis experimentation.

Post-Experiment Questionnaire

1) Did you feel the presentation time of the symbols was long enough? (circle one)

YES NO

2) How much effort do you feel you put into the experiment? (Place and "X" along the line)

|----|----|----|----|----|----|----|----|----|----|
0% 50% 100%

3) Did you perceive any patterns developing in the presentations you received? If yes, please explain.

4) How would you define the task of determining if one symbol was closer than the other? (circle one)

very easy	moderately easy	neutral	moderately difficult	very difficult

5) Do you have any personal comments or impressions concerning the experiment?